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TITANIUM-INDIFFUSED WAVEGUIDES IN MAGNESIUM OXIDE DOPED STOICHIOMETRIC LITHIUM NIOBATE (MgO:SLN)

Ansgar Hellwig, Hubertus Suche, Rebecca Schrör, and Wolfgang Sohler

Angewandte Physik, Universität Paderborn, Warburger Straße 100, 33098 Paderborn, Germany
a.hellwig@physik.upb.de

ABSTRACT

Titanium indiffusion into MgO-doped stoichiometric lithium niobate and the induced refractive index profiles have been investigated at four different wavelengths. Both results yield the polarisation dependent local index change as function of the Ti concentration and its dispersion.

KEYWORDS

waveguide fabrication, stoichiometric lithium niobate, titanium indiffusion

INTRODUCTION

Lithium niobate is an excellent material for the fabrication of integrated optical devices. However, standard congruent $LiNbO_3$ (CLN) suffers from the “optical damage” effect [1], i.e. a light induced change of the refractive index at high intensities, namely for nonlinear optical applications like frequency doubling and sum frequency generation. One possible solution of the problem is to operate devices at elevated temperatures or to use proton exchanged waveguides. The former solution requires a complicated packaging technique whereas the latter one has higher transmission losses and guides only one polarisation. An alternative solution could be to fabricate Ti-diffused waveguides in a lithium niobate substrate, which has a very low photorefractive sensitivity. MgO-doped congruent lithium niobate (MgO:CLN) can have a drastically reduced photorefraction provided the MgO-doping level is 5 mol% or higher [2]. However, inhomogeneities of this material prevent the fabrication of microdomain gratings with the required homogeneity for efficient quasi-phasematched (QPM) nonlinear frequency conversion [3]. On the other hand, stoichiometric lithium niobate (SLN) needs only a very low MgO-doping level of less than 1 mol% to prevent photorefraction [4] resulting in a superior homogeneity. Moreover, in this material the coercive field strength for inversion of ferroelectric microdomains is very low [5]. All these properties make MgO:SLN an attractive substrate material for the fabrication of damage resistant Ti-indiffused waveguides.

In this paper, we report the first detailed characterization of Ti-indiffusion into *Z*-cut MgO:SLN and the optical properties of the fabricated waveguides.

PLANAR WAVEGUIDES

Planar waveguides have been prepared in Z-cut MgO(1 mol%):SLN wafers. Titanium layers were deposited onto the surface by e-beam evaporation. These layers were indiffused at three different temperatures for 19 h in Ar atmosphere and 1 h in O_2 atmosphere to compensate for oxygen losses (see Table 1).

Table 1. Fabrication parameters

Sample	Ti thickness	$T_{diffusion}$
#1	92 nm	1100°C
#2	120 nm	1130°C
#3	120 nm	1150°C

Ti-concentration profile: The depth profile of the titanium concentration was determined using secondary neutral mass spectroscopy (SNMS). The resulting profiles are shown in Fig. 1 on the left. Using a Gaussian fit to the measured profiles the temperature dependent diffusion coefficient *D* can be determined from the 1/e-penetration depth $d_{1/\mathrm{e}} = 2\sqrt{Dt}$, where *t* is the diffusion time. A linear fit of $\ln D$ versus $1/k_\mathrm{B}T$ (Arrhenius plot: $\ln D = -Q/(k_\mathrm{B}T) + \ln D_0$) yields the diffusion constant D_0 = 30.6 cm^2/s and the activation energy Q = 3.72 eV (right diagram of Fig. 1). Fig. 1 also contains for comparison the Arrhenius plots for Ti-diffusion into undoped *Z*-cut CLN and SLN [6–8].

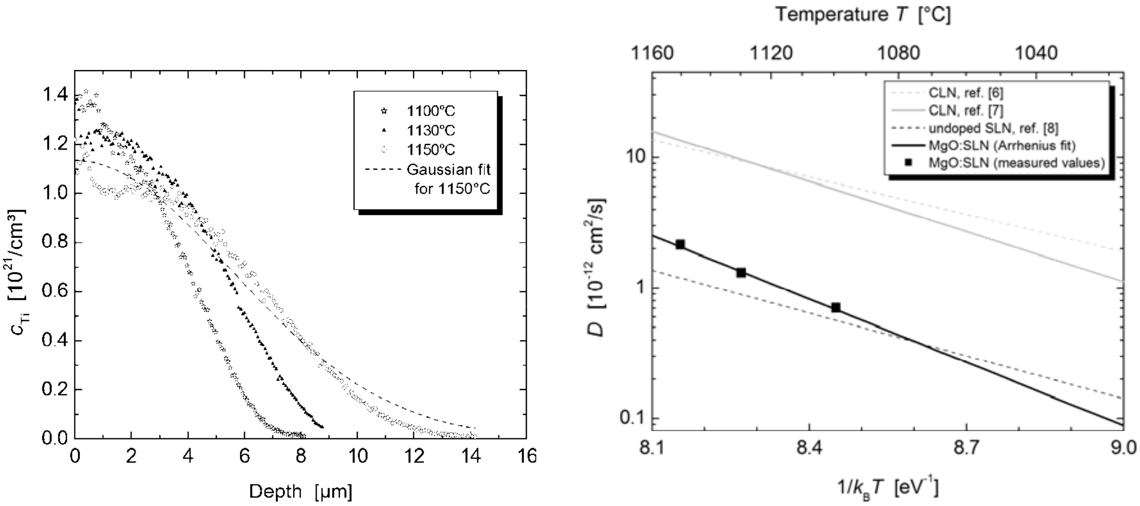


Fig. 1: Left: Titanium concentration profiles for three diffusion temperatures, measured using SNMS. Right: Arrhenius plot of D (logarithmic scale) versus $1/k_BT$; squares: measured diffusion coefficients; black solid line: linear fit; dashed solid line: undoped SLN [8]; grey lines: CLN [6, 7].

Refractive index profiles: The effective refractive indices of the guided modes of the corresponding planar waveguides have been measured using m-line spectroscopy. This measurement was repeated at four different wavelengths, 532 nm, 640 nm, 790 nm, and 1064 nm, respectively. Sample #3, having the deepest titanium concentration profile, is multi-moded at all these wavelengths for both, TM- and TE-polarisation.

The depth profile has approximately been determined by the inverse WKB method [10]. As an example, the resulting profile of sample #3, normalized according to $(n_{\mathrm{eff}}-n_{\mathrm{bulk}})/(n_{\mathrm{surface}}-n_{\mathrm{bulk}})$, is shown in Fig. 2. The measured profiles fit quite well to Gaussian distributions.

A direct comparison of the refractive index profile with the Ti concentration profile allows to determine the wavelength dependent refractive index change as function of the Ti-concentration $\Delta n(c_{\mathrm{Ti}})$. Fig. 3 shows this relation for 640 nm wavelength. Both, ordinary and extraordinary index change can be fitted by a straight line (dotted graphs), indicating that the dependence is almost linear for both polarisations in contrast to the corresponding functions in undoped CLN (solid graphs for comparison [9]). The change of the ordinary index in MgO:SLN is considerably lower than in CLN, whereas the index increase of the extraordinary polarisation is of similar magnitude.

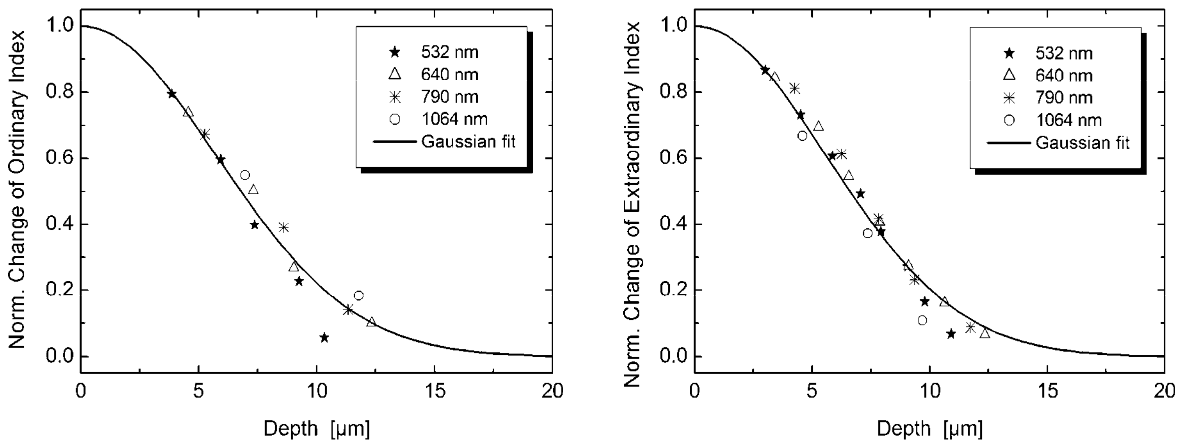


Fig. 2: Profiles of the indices of refraction of sample #3, normalized according to $(n_{\mathrm{eff}}-n_{\mathrm{bulk}})/(n_{\mathrm{surface}}-n_{\mathrm{bulk}})$, versus depth, reconstructed using the inverse WKB-method (symbols: effective refractive indices versus turning points); left: ordinary polarisation (TE), right: extraordinary polarisation (TM); solid lines: Gaussian fit.

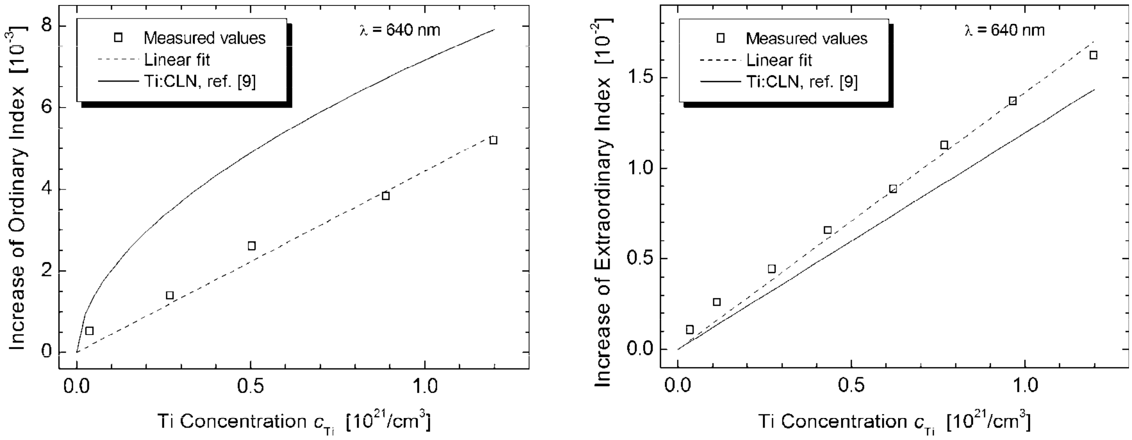


Fig. 3: Refractive index increase of sample #3 at 640 nm wavelength; left: ordinary index; right: extra-ordinary index; symbols: values determined by the iWKB analysis, including surface index; dotted lines: linear fit; solid lines: results for Ti:CLN [9] for comparison.

To obtain the dispersion, i.e. the wavelength dependence of the refractive index increase, we have fitted the maximum index change $n_{\text{surface}}-n_{\text{bulk}}$ to an oscillator term (see Fig. 4). Using this fit, the refractive index change can be expressed as a function of Ti-concentration and wavelength. The wavelength λ has to be inserted in units of [nm].

$$\Delta n_{\text{o}}(\lambda) = 2.29\times 10^{-24}\,\tfrac{1}{cm^3}\,\frac{c_{\text{Ti}}\ \lambda^2}{\lambda^2 - 1.26\times 10^5} \qquad \Delta n_{\text{e}}(\lambda) = 9.68\times 10^{-24}\,\tfrac{1}{cm^3}\,\frac{c_{\text{Ti}}\ \lambda^2}{\lambda^2 - 9\times 10^4}$$

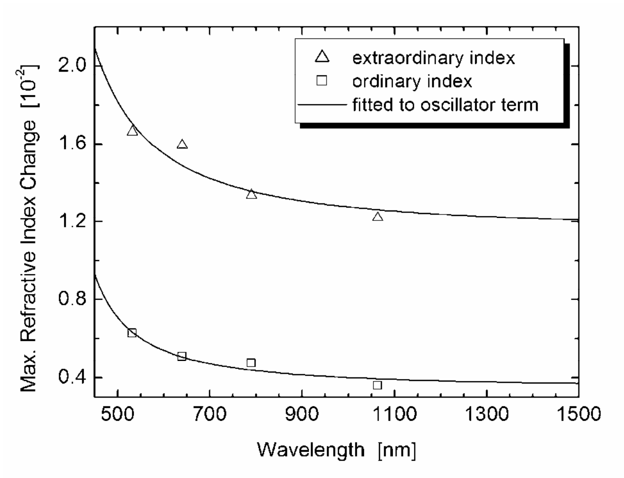
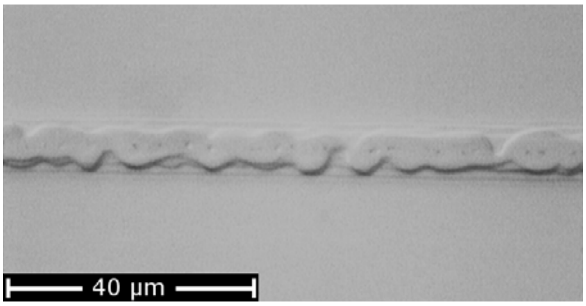


Fig. 4: Wavelength dependence of refractive index increase on wavelength, for both polarisations

STRIP WAVEGUIDES

Based on the results obtained by the development of planar waveguides we fabricated monomode strip waveguides for λ ~ 1550 nm. Fig. 5 shows our first experimental results. On the left the surface morphology after indiffusion (30 h, 1100°C) of a photolithographically delineated 7 µm wide, 98 nm thick Ti-stripe has been visualized using differential interference contrast microscopy. The quality is not yet comparable to the one of undoped Ti:CLN waveguides. This is also confirmed by the waveguide losses of ~ 0.5 dB/cm for TM polarised light at 1550 nm, measured using the low finesse Fabry-Pérot method [11]. On the right of Fig. 5 the measured near field intensity distribution of the TM-mode at 1550 nm wavelength is shown. As indicated, the FWHM is 2.7 µm perpendicular and 4.3 µm parallel to the substrate surface. The size of the TE-mode is significantly larger (~ 23×22 µm) due to the weaker guiding strength for this polarisation.



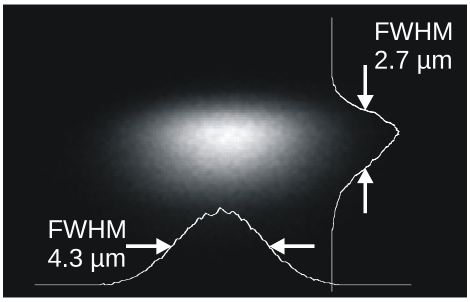


Fig. 5: Ti-diffused channel waveguide in MgO:SLN; left: surface morphology, right: near field intensity distribution of the TM mode at 1550 nm wavelength.

CONCLUSION

Titanium indiffusion into MgO-doped SLN and the resulting optical properties have been investigated. It turns out that the diffusivity of titanium is drastically reduced in comparison to indiffusion into undoped CLN.

The local Ti-concentration leads to a wavelength dependent, almost linear increase of the refractive index for both polarisations. The increase of the ordinary index is significantly lower than in CLN. By fitting the index increase to a single oscillator term, analytical expressions for the dispersion of the induced index change have been derived. The increase of the extraordinary index, which is the important one for QPM nonlinear frequency conversion, is nearly the same as for Ti:CLN.

First strip waveguides have been fabricated, still showing a higher loss and worse surface morphology in comparison with Ti:CLN-waveguides. The diffusion conditions still have to be refined to fabricate high quality, optical damage resistant devices in the future. The photorefractive sensitivity of these waveguides is currently being investigated.

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